Blockage Correctors and Their Appraisal

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Summary

The studies on blockage effect are historically reviewed by dividing them into the three stages, such as "initial", "devolopmental" and "applicable" ones.

The twelve blockage correctors are referred in this report, which were published mainly in the "applicable stage" in order to correct the blockage effect of model test results obtained in a towing tank. The nine correctors, out of twelve, are applied to the experimental data, which were obtained in the Nagasaki Tank, MHI, compared with each other and evaluated their effectiveness.

1. Introduction

When a model is towed in a towing tank, the measured values are somewhat different from those which would be obtained on such an unrestricted water like sea, if one adopts a larger model for the tank size. This effect comes from that tank sides and bottom prevent the flow around the model and is called the "blockage effect".

It has been one of the most important and basic problems for tankery people to find out the limit of its occurrence and the method how to correct it. Since it is usual to choose the size of a model as large as possible from the view point of the accuracy of measurements. Furthermore, it is inevitable to make clear them when one intends to compare the test results of geosim models or of the same model in the different tanks and also to correlate the ship-model correlation factors with those derived from other tanks.

Many researchers have made both theoretical and experimental studies and proposed "blockage correctors" of their own. ITTC also made recommendations several times and stimulated to present a satisfactory blockage correction method through both Resistance and Powering Performance Committees.

It must be regrettable that the studies on this theme seems to be depressed after nineteen-eighties. Its importance, however, does never decrease. The author sincerely hopes that the studies on this theme should be prompted again by applying such a new technology as CFD and so on.

In the present report, the author reviews at first the studies on blockage effect historically. Then, he refers many blockage correctors which may be applicable to correct the model test results and

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evaluates its effectiveness by comparing with the experimental data.

2. Basic Concept of the Correction of Blockage Effect and the Historical Review of Its Study

Through a historical review of the studies on blockage effect they can be classified into the following three stages.

(I) **Initial stage** (before 1940)
The study was made either experimentally or theoretically and confirmed the blockage effect. But the application to correct the blockage effect of model test results was not yet considered.

(II) **Developmental stage** (1941~1957)
Experimental studies were made systematically. Several correction methods (or formulae) were proposed based on these experimental data.

(III) **Applicable stage** (after 1958)
Correction formulae were developed based on some theoretical considerations and modifications were made so as to fit in with the experimental data, if necessary. The formulae thus derived would be applicable for the correction of model test results.

In parallel with these studies on blockage effect, both the shallow water effect (where only water depth is limited) and the restricted water effect (where both water breadth and depth are limited) on wave resistance of a body are analyzed theoretically, in keeping step with the advancement of the wave resistance theory. The basic studies in this field were almost completed within the "developmental stage" defined above. The tasks here after might be to conduct supplementary studies and to increase the calculation range and cases by use of computer. It is doubtless that the studies stated here gave definite influence on the derivation of blockage correctors.

The correction method of blockage effect can be divided on the whole into the following categories.

1) Correction is made on resistance of a model directly.
2) Correction is made on water velocity, as the resistance of a model is changed due to the increase of water velocity around it.

For each of the above categories, the following three concepts can be applicable. Namely,

a) Correction is made on total resistance only,
b) Correction is made at first on total resistance so as to compensate the velocity increase due to blockage effect, then further correction is applied on wave resistance component due to shallow water and side-walls effects, and
c) Correction is made on viscous resistance component so as to compensate the velocity increase due to blockage effect and wave resistance component due to shallow water and side-wall effects separately.

In order to investigate the blockage effect on a model experimentally, it is a common idea to conduct resistance tests of the same model in the tanks of different cross sections. Lamb [I -2], Yamagata [I -4] and Hiraga [I -5] carried out this kind of tests respectively by sending a model to different tanks at the time of "initial stage".

It is doubtful, however, whether the difference of the test results thus obtained shows true feature of blockage effect or not. There are so many items, which may cause erros in the test results obtained in the different tanks, as water temperature, deformation of model, model surface condition, adjustment of test condition of model, testing equipment such as towing carriage, measuring dynamometer, velocity measurement, recorder etc., test procedure and test sequence, shape of tank cross section and so on.

To reduce such probable errors, the experimental studies at the time of "developmental stage" and thereafter were conducted mainly in th same tank by either towing a model in different cross sections which were made tentatively by use of false bottom and walls or towing the geometrically similar models with different sizes. The former method was applied by Landweber [I -8], Comstock-Hancock [II-1], Emerson [III-2], Kim [III-4] etc., and the latter by Conn et al [II-5], van Lammern [II-7], Hughes [II-10] etc.

The experimental studies by use of the mirror effect were also applied by van Lammern et al [II-7], van Manen-van Lammern [II-9], Graff [III-6] etc. Where some number of similar models with the same size were arranged transversely in a tank and towed at the same time with the same velocity. The resistance of one of these models was measured and compared by changing the number of models.

The methods stated above, however, still have their own advantages and defects respectively. It was thought rather hard to conduct experiments precisely in order to get blockage effect. In this connection, the experiments made in the Nagasaki Tank, MHI have been regarded as the most important and useful. Its towing tank consists of two sections, i.e. the larger (wider) and the smaller (narrower) tanks are connected longitudinally and the towing carriage of the larger one can run over the length of both tanks. The difference of the resistance and the sinkage of a model due to the difference of blockage effect of both tanks can be measured with high reliability and accuracy by towing it through both tanks at a time. Thus, the experimental results obtained by Taniguchi-Tamura [II-6] and Tamura [III-9] [III-10] have got high values of appreciation.

On the other hand, it was thought also effective to find out blockage effect through the statistic analysis of the large amount of experimental data instead of getting precise experimental results. Hughes [III-3], Scott [III-5] [III-7] [III-8] [III-15] etc. derived their blockage corretors by this procedure.

Based on these experimental studies as stated above, the blockage correction was mainly applied to resistance, i.e. either total resistance or viscous resistance component, directly until the time of "developmental stage". For example, Comstock-Hancock [II-1] and Taniguchi-Tamura [II-6] applied the blockage correction to total resistance of a model. While van Manen-van Lammern [II-9], Hughes [II-10] and Telfer [II-4], who analyzed the experimental results given by Conn et al, proposed the correction for viscous resistance component.

In the case of theoretical treatment, it was rather hard to evaluate the blockage effect for resistance directly, except for wave resistance component. Therefore, it was common procedure to evaluate the velocity increase on a model surface due to blockage effect and to correlate it with resistance through the relation, $R \propto U^n$. It may be said that the theoretical studies substantially belong to category 2) as defined before.

There are two kinds of concept to evaluate the velocity increase on a model surface theoretically. The one is to evaluate it under the assumption that water flows inside a solid wall~like a wind tunnel. This is called as "back flow theory". The other is to evaluate it taking the depression of water surface by the presence of a model into account under the assumption that water flows uniformly across the tank section. This is called as "mean flow theory".

The "back flow theory" was introduced and developed by Lamb [I -2], Lock [I -3], Yamagata [I -4], Young-Squire [II-2] etc. at the time of "initial stage" and "developmental stage". The "mean flow theory" was introduced by Krey [I -1] and Kreitner [I -6] at the time of "initial stage", and utilized by van Lammern et al [II-3], Conn et al [II-3], Schuster [II-8] etc. at the time of "developmental stage".

The former theory has such substantial weak point as to oppose the physical phenomenon, since it is based on the assumption that the depression of water surface by the presence of a model is disregarded. The latter one has also such weak point that the value of velocity increase can not be correlated with the hull form of a model. Thus, it was thought that an experimental correlation in any kind was inevitable for both cases.

The blockage correctors developed in the "applicable stage" were on the whole such type that the velocity of a model was corrected by either "back flow" or "mean flow" theories. The Schuster's correction [II-8] for shallow water effect and/or experimental correction were applied further, if necessary.

Taniguchi-Tamura [III-1], Scott [III-7] [III-8] and Ogiwara [III-13] developed correctors based on "back flow theory". Emerson [III-2], Hughes [III-3] and Kim [III-4] developed correctors based on "mean flow theory". Furthermore, Tamura [III-9] [III-10] [III-12] developed a corrector by combining the both theories. Scott [III-5] [III-15] and Landweber-Nakayama [III-14] proposed correctors which took the effect of both theories into consideration.

It is usual that the blockage correctors thus developed are to be applicable to such a tank cross section as water breadth depth ratio is about two. Tamura [IV-1], however, applied his corrector to the resistance test results in shallow water, where the water breadth depth ratio was far larger than two. He showed that it was necessary to correct the blockage effect even on the shallow water test results and his corrector was applicable even in this case. He also showed there existed blockage effect even in such an extreme case where water breadth was infinitive while water depth was shallow (blockage =0) and a kind of virtual blockage should be considered.

The application of a blockage corrector to shallow water bounderies as proposed by Tamura will be important for the analysis of shallow water test results. Further study on this theme is very much awaited. In the present report, however, the review of blockage corrector is to be confined within an ordinary shape of tank cross section.

In the next chapter, the explanation is given on each blockage corrector developed in the "applicable stage".

3. Blockage Corrector Applied for Practical Use

3. 1. Blockage Corrector Based on the Mean Flow Theory

3. 1. 1 Mean Flow Theory

When a model with midship section area A_M is towed through a tank with the cross section of water breadth b and water depth h, the water velocity (towing velocity) U is to be increased by $\triangle U$ and water surface is to be reduced by $\triangle h$. Then, by the law of continuity, the following equation is given;

$$\frac{\triangle U+U}{U}=\frac{bh}{bh-b\triangle h-A_M}, \tag{1}$$

or

$$\frac{\triangle U}{U}=\frac{m+\dfrac{\triangle h}{h}}{1-m-\dfrac{\triangle h}{h}}. \tag{1'}$$

Where, m=blockage$=A_M/bh=A_M/A_T$,

$A_T=bh$=cross sectional area of a tank.

With the aide of Bernoulli's theorem, the following equation is given;

$$\triangle h=\frac{(U+\triangle U)^2}{2g}-\frac{U^2}{2g}, \tag{2}$$

or

$$\frac{\triangle h}{h}=F_h^2\left[\frac{\triangle U}{U}+\frac{1}{2}\left(\frac{\triangle U}{U}\right)^2\right], \tag{2'}$$

Where, $F_h=U/\sqrt{gh}$; Froude number defined by water depth.

From (1') & (2'),

$$\frac{1}{2}F_h^2\left(\frac{\triangle U}{U}\right)^3+\frac{3}{2}F_h^2\left(\frac{\triangle U}{U}\right)^2-(1-m-F_h^2)\left(\frac{\triangle U}{U}\right)+m=0. \tag{3}$$

Taking that $\left(\frac{\triangle U}{U}\right)$ is smaller value into consideration, the higher order of $\left(\frac{\triangle U}{U}\right)$ is to be omitted. Then, the following equation of mean flow theory is derived.

$$\frac{\triangle U}{U}=\frac{m}{1-m-F_h^2}. \tag{4}$$

3. 1. 2 Schuster's Corrector [II-8]

$$\frac{\triangle U}{U}=\frac{m_1}{1-m_1-F_h^2}+\left(1-\frac{R_V}{R_T}\right)\frac{2}{3}F_h^{10}. \tag{5}$$

Where, m_1=blockage for the maximum (midship) sectional area of a model

$=A_M/A_T$,

R_t & R_V=Total and viscous resistance of a model respectively at velocity U.

The first term of the above equation is the same as that given by the mean flow theory (eq. (4)). The second term is the correction for wave resistance due to shallow water effect. This was derived by Schuster under the assumption of Schlichting [I-7].

The Schuster's corrector consists of solely theoretical considerations and no experimental correction is applied.

3. 1. 3 Emerson's Corrector [III-2]

$$\frac{\triangle U}{U}=K\cdot\frac{m_3}{1-m_3-F_h^2}. \tag{6}$$

Where, $m_3=1/2(m_1+m_2)$,

m_2=blockage for the mean sectiona area of a model

$=\frac{\nabla}{LA_T}=C_p\frac{A_M}{A_T}=C_p\cdot m_1$,

C_p=prismatic coefficient of a model,

K=a correction factor.

Emerson gave K=1.65 through the analysis of the model test results obtained in King's College Tank, No. 1 Tank of NPL and St. Albans Tank.

3. 1. 4 Hughes' Corrector [III-3]

$$\frac{\triangle U}{U}=k\left[\frac{m_2}{1-m_2-F_h^2}+\frac{n_W R_W}{n_T R_T}\left(\frac{\triangle U}{U}\right)_h\right]. \tag{7}$$

Where, R_T & R_W=total and wave resistance of a model respectively at volocity U,

n_T & n_W=exponent of U which shows the rate of change of total and wave resistance by U respectively near velocity U, ($R\propto U^n$).

k= a correction factor.

The first term of the above equation is the same as that given by the mean flow theory (eq. (4)). Hughes adopted m_2 for blockage and also adopted correction factor k at the same time. The second term is the correction for wave resistance due to shallow water effect. $\left(\frac{\triangle U}{U}\right)_h$ was given by the following formula;

$$1+\left(\frac{\triangle U}{U}\right)_h=\sqrt{\cot\frac{1}{F_h^2}}. \tag{8}$$

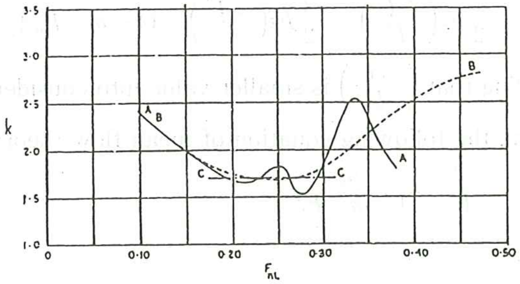

Fig. 1 Recommended Values of k for Models of Average N.P.L. size (Hughes)

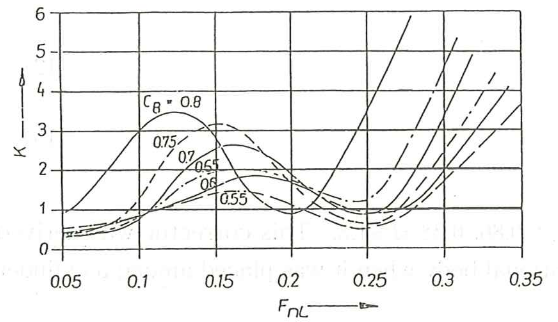

Fig. 2 Curves of K Factors (Kim)

Or by use of Schuster's approximation given in eq. (5);

$$\left(\frac{\triangle U}{U}\right)_h \doteqdot \frac{2}{3} F_n^{10}. \quad (9)$$

Hughes gave k as a function of Froude number through the analysis of model test results obtained in No. 1 & 2 Tanks of NPL. The value of k thus analyzed is given in Fig. 1. He also gave $k=1.7$ as an approximation within the range of Froude number; $0.17<F_n<0.30$. Where F_n is the Froude number defined by model length.

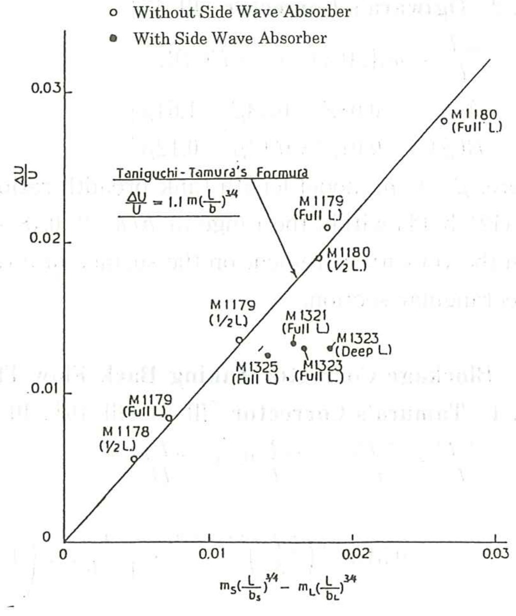

Fig. 3 Results of Analysis on Blockage Effect

3. 1. 5 Kim's Corrector [III-4]

$$\frac{\triangle U}{U} = K \cdot \frac{m_2}{1-m_2-F_h^2}. \quad (10)$$

Where, K is a correction factor. Kim gave K as a function of block coefficient C_b and Froude number F_n, as shown in Fig. 2. This was derived through the analysis of model test results obtained in the tank of Michigan University.

3. 2 Blockage Corrector Based on the Back Flow Theory

3. 2. 1 Taniguchi-Tamura's Corrector [III-1]

$$\frac{\triangle U}{U} = 1.1 m_1 \left(\frac{L}{b}\right)^{3/4}. \quad (11)$$

Where, L=length of a model (water line length),

b=breadth of a tank (water breadth).

This corrector was derived from the difference of the velocity on the surface at the maximum section of Rankine ovoid [I -2] caused with and without a rigid circular cylinder wall surrounding it. A correction factor was applied to the corrector, which was determined by the test data of the Nagasaki Tank, MHI as shown in Fig. 3.

3. 2. 2 Ogiwara's Corrector [III-13]

$$\frac{\triangle U}{U}=m_1\{A(\beta)\cdot C_p+B(\beta)\}, \tag{12}$$

$$\left.\begin{array}{l}A(\beta)=-0.08\beta^3-0.33\beta^2+1.64\beta\\ B(\beta)=-0.01\beta^3+0.13\beta^2-0.12\beta\end{array}\right\}. \tag{13}$$

Where, $\beta=L/b$, model length tank breadth ratio.

Eq. (12) holds within the range of $b/h=2$, $0.48\leqq C_p\leqq 0.86$, $0.2\leqq\beta\leqq 1.8$. This corrector was derived from the velocity increment on the surface of a rotational body when it was placed among a cylinder of rectangular section.

3. 3 Blockage Corrector Taking Back Flow Theory and Mean Flow Theory into Consideration

3. 3. 1 Tamura's Corrector [III-9] [III-10] [III-12]

$$\frac{\triangle U}{U}=\frac{\triangle U_1}{U}+\frac{\triangle U_{h1}}{U}+\frac{\triangle U_{h2}}{U}$$

$$=0.51m_1^{1.05}\left(\frac{2L}{b}\right)^{0.8-4.76m_1}\cdot\frac{1}{1-F_h^2}+\left(1-\frac{\frac{dR_V}{dU}}{\frac{dR_T}{dU}}\right)\frac{2}{3}F_h^{10}+\left(\frac{1-\frac{R_V}{R_T}}{\frac{dR_T}{dU}\cdot\frac{U}{R_T}}\right)25F_h^{12}. \tag{14}$$

Where, R_V=viscous resistance of a model.

At first Tamura proposed the blockage corrector as shown in eq. (14) [III-9] [III-10]. The first term of the equation is the basic one obtained through the theoretical treatment starting from Rankine ovoid in a rigid circular cylinder [I -2], which is the same as the Taniguchi-Tamura's corrector [III -1], and the effect of the depression of water surface is taken into account by $1/(1-F_h^2)$. This velocity increase is due to potential flow and to be applied for all resistance components.

The second term is the correction for shallow water effect on wave length given by Schuster, which is to be applied on wave resistance component only. This correction is derived under the assumption that the wave resitance in the shallow water at a given velocity will be the same as that in the deep water at the equivalent velocity which causes the same wave length as in the shallow water. The third term is the correction for shallow water efffect on wave amplitude which is also to be applied on wave resistance component only.

Later, Tamura added the fourth term to eq. (14), which gave the correction for side wall effect on wave resistance [III-12], as shown below.

$$\frac{\triangle U_b}{U}=\frac{\triangle R_{Wb}}{U\cdot\frac{dR_T}{dU}}. \tag{15}$$

Where, $\triangle R_{Wb}=R_{Wb}-R_{W\infty}$,

R_{Wb}=wave resistance for finite water breadth,

$R_{W\infty}$=wave resistance for infinite water breadth.

The calculation of wave resistance is to be made by use of amplitude function derived from the wave pattern analysis of the model.

3. 3. 2 Landweber-Nakayama's Corrector [III-14]

$$C_T(R_n, F_n, 0)=\frac{C_T(R_n, F_n, m_1)}{(1+u_1)^2}+\{C_V(R_n, 0)-C_V(R'_n, 0)\}$$
$$-2u_1\frac{A_S}{S}+\left[\left(\frac{C'_{W\infty}}{C'_{Wb}}\right)_{\text{cal}}-1\right]\frac{C_W(F_n, m_1)}{(1+u_1)^2}. \quad (16)$$

Where, $C_T(R_n, F_n, 0)$, $C_T(R_n, F_n, m_1)$=total resistance coefficient of blockage zero and m_1 respectively at Reynolds number R_n and Froude number F_n.

$C_V(R_n, 0)$=viscous resistance coefficient at R_n and blockage zero,

$C_W(F_n, m_1)$=wave resistance coefficient at F_n and blockage m_1,

A_S=projected area on the body plan of a model where separation of flow occurs. (this area should be assumed properly).

$(C'_W/C'_{Wb})_{\text{cal}}$=ratio of the calculated wave resistance without and with side walls of a water way, (this ratio, calculated by linear theory, is given in the diagrams for easy application),

$R'_n=R_n(1+u_1)$

u_1=rate of velocity increment on a model surface due to blockage effect.

u_1 is to be calculated by the following formulae:

$$u_1=\frac{u_0}{1-u_0}, \quad (17)$$

$$u_0=u_{01}+u_{02}+u_{03}$$
$$=0.25\frac{A'_M\cdot C_P^{2/3}}{r_E'^{2.7}}\left[1+\frac{2.7}{r'_E}\cdot\frac{C_P\cdot m_1\cdot h'\cdot F_h^2}{1-F_h^2}+\frac{B'}{A'_M}F_n^2\cdot f(B', T')\right]. \quad (18)$$

Where, u_{01}=velocity increment on a body surface when it is placed inside a circular cylinder (back flow theory),

u_{02}=correction for the effect caused by the depression of water surface,

u_{03}=correction for the increment of the dipping of a model due to blockage effect,

$A'_M=A_M/L^2$, $r'_E=r_E/L$, $b'=b/L$, $h'=h/L$, $T'=T/L$ (T=draft of model).

"r_E" is the radius of a circular cylinder (side wall). When the cross sectional form is different from a circle, "r_E" should be assumed by replacing it to the equivalent circular cylinder. When the cross sectional form is a rectangle, "r_E" is to be calculated by the following formula;

$$\frac{1}{r_E}=1.15\left(\frac{1}{b'}+\frac{1}{2h'}\right)-\frac{0.55}{\sqrt{2b'h'}}-0.070\left(\frac{1}{b'}-\frac{1}{2h'}\right). \quad (19)$$

The value of $f(B', T')$ is given in the following table;

B'/T'	$L/T=10$	$L/T=16$
1	0.0253	0.0138
2	0.0453	0.0231
3	0.0612	0.0318
4	0.0735	0.0397

3. 3. 3 Scott's Correctors

Scott developed correctors one after another through the statistic analysis of the experimental data of the St. Albans Tank, No. 1 & No. 2 Tanks of NPL, and, furthermore, of the Nagasaki Tank, MHI, since 1966.

The basic term of his corrector is the following formula given by Young-Squire [II-2] for a blockage correction of wind tunnel test results.

$$\frac{\triangle U}{U}=C\cdot\frac{\nabla}{A_T^{3/2}}. \tag{20}$$

Eq. (20) can be rewritten as;

$$\frac{\triangle U}{U}=C'\cdot m_2\cdot\left(\frac{L}{b}\right). \tag{21}$$

Where C & C' are coefficients.

The formula given by Young-Squire is derived from the back flow theory, where the effect of the depression of water surface is not taken into account. Therefore, Scott applied a certain correction for the depression of water surface to his No. 1 corrector. He deleted this correction term in his No. 2 and 3 correctors and recovered again in his No. 4 corrector.

Also, Scott thought the effect of Reynolds' number very important to the blockage effect. In the following, Scott's correctors are given.

(a) **Scott's No. 1 Corrector** [III-5]

$$\frac{\triangle U}{U}=0.51(\nabla+L^3C)A_r^{-3/2}(1-0.35F_h^2)^{-3/2}+\left(1-\frac{1.82C_v}{n_tC_t}\right)f_{(F_h)}. \tag{21}$$

And,

$$\left.\begin{aligned} f_{(F_h)}&=0.239(F_h^2-0.25)(1+F_h^2) && \text{for } 0.25<F_h^2<0.55\\ &=0 && \text{for } F_h^2<0.25 \end{aligned}\right\} \tag{22}$$

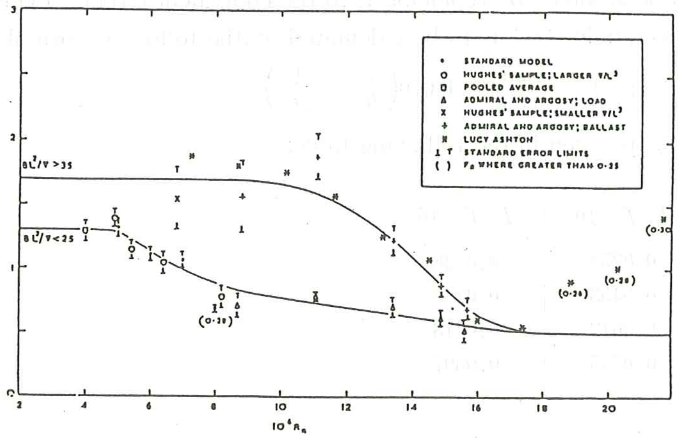

Fig. 4 Variation of Blockage Factor b with Reynlods Number and BL^2/∇ (Scott No. 2 Corrector)

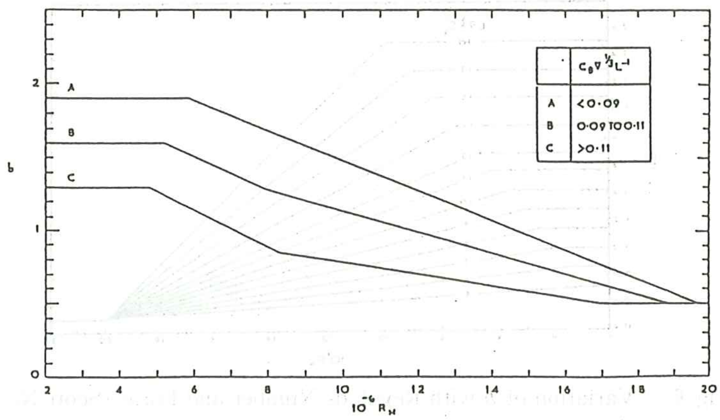

Fig. 5 Variation of Blockage Factor b with Reynlods Number (Scott No. 3 Corrector)

$$10^3 C = 9.2 - 0.015(R_n \cdot 10^{-6})^3 \quad \text{for } R_n < 8\times10^6$$
$$= \frac{12}{(R_n \cdot 10^{-6})}. \quad \text{for } R_n > 8\times10^6 \tag{23}$$

Where, R_n=Reynolds' number of a model,

C_t & C_v=total and frictional resistance coefficients respectively,

n_t=exponent of U which shows the rate of change of the total resistance coefficient C_t by U near the velocity U.

Scott corrected the effect of the depression of water surface by reducing the cross sectional area of a tank from A_T to $A_T\left(1-\frac{\triangle h}{h}\right)$. He gave the following formula instead of eq. (2).

$$\frac{\triangle h}{h} = \frac{(U_u + \triangle U)^2}{2gh} - \frac{U^2}{2gh}. \tag{24}$$

Where, U_u is the mean velocity of flow on the surface of a model without any boundaries such as bottom and side-walls. He assumed $U_u/U \fallingdotseq 1.3$, obtained the following formula approximately and applied it to the first term of eq. (21).

$$\frac{\triangle h}{h} \fallingdotseq \frac{1}{2} \cdot \frac{U^2}{gh}\left\{\left(\frac{U_u}{U}\right)^2 - 1\right\} \fallingdotseq 0.35\frac{U^2}{gh}. \tag{24'}$$

(b) **Scott's No. 2 Corrector** [III-7]

$$\frac{\triangle U}{U} = b \cdot \nabla \cdot A_T^{-3/2}. \tag{25}$$

Where, b is a correction factor derived from the statistical analysis of experimental data and given in Fig. 4.

(c) **Scott's No. 3 Corrector** [III-8]

$$\frac{\triangle U}{U} = b\nabla A_T^{-3/2} + BL^2 f_{(F_{nL})} A_T^{-3/2}, \tag{26}$$

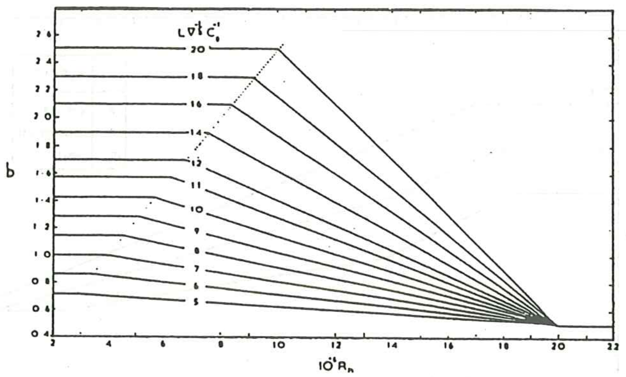

Fig. 6 Variation of b with Reynlods Number and Form (Scott No. 4 Corrector)

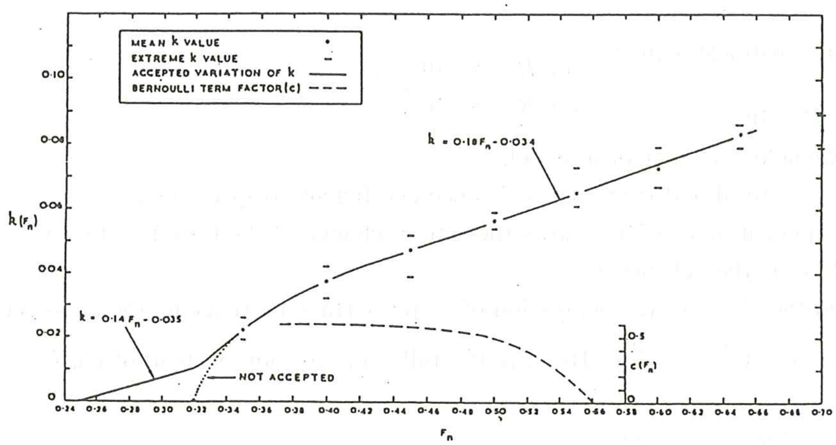

Fig. 7 Variation of k and c with Froude Number (Scott No. 4 Corrector)

$$\left.\begin{aligned} f_{(F_{nL})} &= 2.4(F_{nL}-0.22)^2 \quad \text{for } F_{nL}>0.22 \\ &= 0. \qquad\qquad\qquad\quad \text{for } A_{nL}<0.22 \end{aligned}\right\} \tag{27}$$

Where, b is a correction factor as given in Fig. 5, which shows the effect of Reynolds' number and is derived from the statistical analysis of experiments. This corrector was reported to the Performance Committee of the 13th ITTC and evaluated by the Committee [III-11].

It was recommended at the 13th ITTC that "the blockage corrector proposed Scott fits the data better, in most cases, than other method tried and may be used——until a more acceptable rational method has been evolved".

(d) **Scott's No. 4 Corrector** [III-15]

This corrector was published in 1975 through RINA. Scott gave it this time in the form of $\triangle C_t$, a correction to the total resistance C_t, as in the following, while his former correctors were whole in the form of $\triangle U/U$.

Table 1. Particulars of Models

Model. No.			M. 1719	M. 1720	M. 1722	M. 2058
Type of hull form			Wibley's parabolic form	Do.	Pien's form	Ore carrier
Length between perpendiculars		Lpp	8.000 m	5.000 m	6.500 m	8.000 m
Length of water line		L	7.984 m	4.990 m	6.510 m	8.165 m
Breadth		B	0.800 m	0.500 m	1.1168m	1.171 m
Draft		T	0.500 m	0.3125m	0.423 m	0.450 m
Trim			0	0	0	0
Volume of displacement		∇	1.422 m³	0.347 m³	1.709 m³	3.486 m³
Wetted surface area		S	9.408 m²	3.675 m²	8.614 m²	14.500m²
Block coefficient (WL)		C_b	0.4453	Do.	0.5558	0.8093
Prismatic coefficient (WL)		C_p	0.6680	Do.	0.5854	0.8147
Midship area coefficient		C_m	0.6667	Do.	0.9495	0.9934
Maximum sectional area		A_M	0.2667m²	0.1042m²	0.4486m²	0.5238m²
Blockage	Larger tank	m_1	0.00340	0.00133	0.00573	0.00669
		m_2	0.00227	0.00089	0.00335	0.00545
	Smaller tank	m_1	0.01232	0.00481	0.02072	0.02419
		m_2	0.00823	0.00321	0.01213	0.01971

$$\triangle C_t=\{n_t \cdot C_t \cdot b\nabla A_T^{-3/2}+k \cdot f \cdot (1+kf)^{-1}C_W\}(1-CF_h^2)^{-1} \tag{28}$$

Where, $\dfrac{\triangle C_W}{C_{W\infty}}=k \cdot f,\ f=\dfrac{L^4(BT)^{1/4}}{A_T^{1.25} \cdot h^2},\ \triangle C_W=C_W-C_{W\infty},$

C_W & $C_{W\infty}$=wave resistance coefficients $(R_w/\frac{1}{2}\rho U^2S)$ of a model in restricted and unrestricted water ways respectively at the velocity U,

b=a correction factor as given in Fig. 6, which shows the effect of Reynolds' number and is derived from the statistical analysis of experiments,

k & C=correction factors as given in Fig. 7 respectively and the former shows the effect of a restricted water way on wave resistance, while the latter is an experimental correction for the effect of the depression of water surface.

4. Apraisal of Blockage Correctors in Comparison with the Experiments

The correction for velocity, $\triangle U/U$ are calculated by use of nine blockage correctors explained in the previous chapter and compared with experiments. These are that of Schuster (eq. (5)), Emerson (eq. (6)), Hughes (eq. (7)), Kim (eq. (10)), Taniguchi-Tamura (eq. (11)), Ogiwara (eq. (12)), Tamura (eq. (14)), Landweber-Nakayama (eq. (16)) and Scott No. 3 (eq. (26)) respectively.

In the case of Tamura's corrector, both the first term only and the total terms of eq. (14) are calculated.

In the case of Landweber-Nakayama's corrector, the first term only is adopted and $\triangle U/U$ is represented by u_1, since both become identical in definition. Because, the second term gives only very small value due to its higher order component and the third term also the same when m_1 is small. The fourth term can not be neglected in the zone where wave resistance becomes significant. At the present comparison, however, this is omitted for the sake of simplicity because the correction on wave resistance is not necessarily needed to grasp the hole tendency of the correction.

As the representative of Scott's correctrs, No. 3 is selected since this was recommended for use by the 13th ITTC.

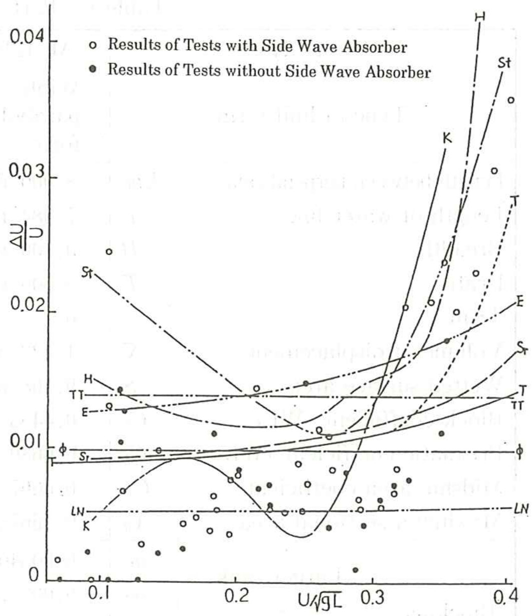

Fig. 8 Comparison of Speed Increase due to Blockage Effect Calculated by Blockage Correctors and Obtained by Model Tests on M. 1719

The four models are used for this comparative calculation, the principal particulars of which are given in Table-1. M. 1719 and M. 1720 are geosim models of the Wigley's parabolic form, which is adopted as a typical hull form of large wave resistance with clear humps and hollows. M. 1722 is a similar model of DTMB M. 4996 proposed by Pien [IV-2], which is adopted as a typical hull form of small wave resistance. While M. 2058 is a ore-carrier model and adopted as a typical hull form with large block coefficient.

These models were towed through the smaller (narrow) and the larger (wide) tanks of Nagasaki Tank, MHI at a time. The difference of resistance due to the difference of blockage effect was obtained precisely [III-9] [III-10].

In Fig. 8 through 11, the difference of the velocity, which gives the same resistance at both tanks,

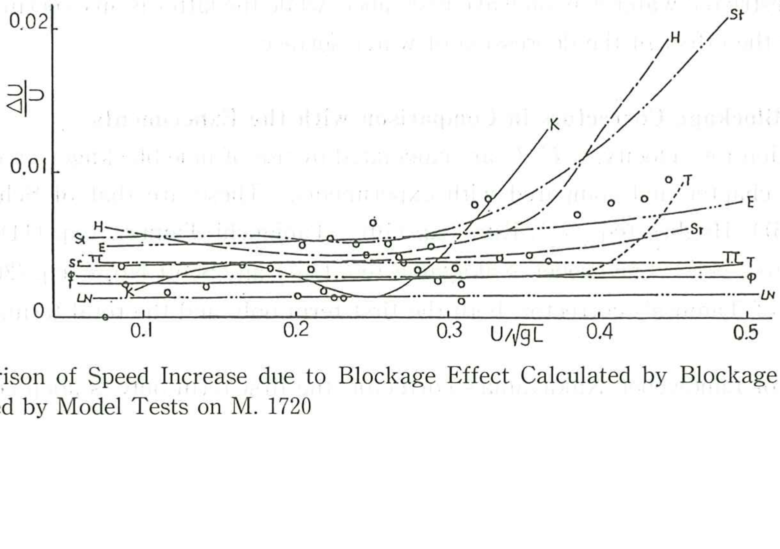

Fig. 9 Comparison of Speed Increase due to Blockage Effect Calculated by Blockage Correctors and Obtained by Model Tests on M. 1720

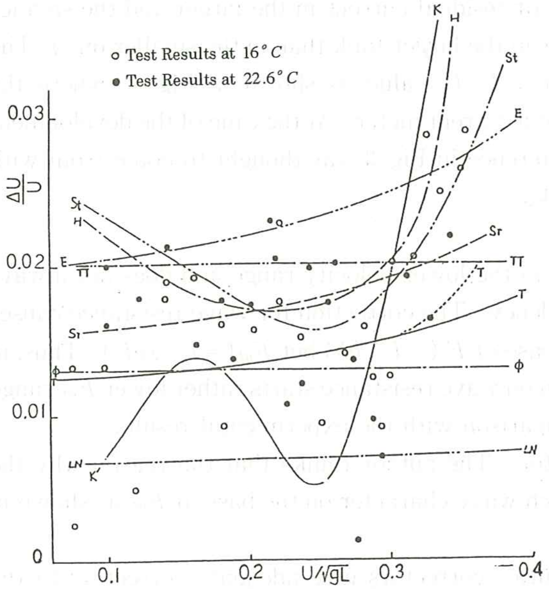

Fig. 10 Comparison of Speed Increase due to Blockage Effect Calculated by Blockage Correctors and Obtained by Model Tests on M. 1.722

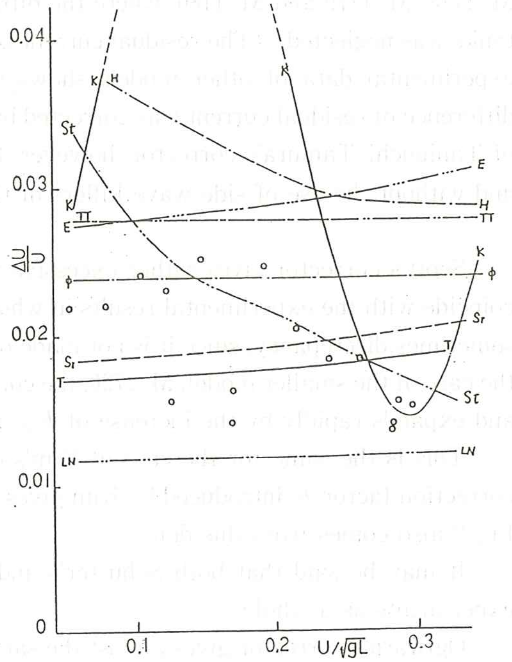

Fig. 11 Comparison of Speed Increase due to Blockage Effect Calculated by Blockage Correctors and Obtained by Model Tests on M. 2058

is shown together with that calculated by the use of nine correctors. The signs of these correctors in the figures are as follows:

Sr	Schuster, eq. (5)
E	Emerson, eq. (6)
H	Hughes, eq. (7)
K	Kim, eq. (10)
TT	Taniguchi-Tamura, eq. (11)
O	Ogiwara, eq. (12)
T	Tamura, first term of eq. (14)
T	Tamura, whole terms of eq. (14)
LN	Landweber-Nakayama, u_1 of eq. (17)
St	Scott No. 3, eq. (26)

It is observed from Fig. 8 through 11 that Emerson's corrector gives the largest correction, then Taniguchi-Tamura's and Hughes' correctors follow. These values show as if they are an envelope of the experimental data in the larger side.

The reason why Taniguchi-Tamura's corrector gives such a larger value of correction may come from that the experimental correction has been applied by use of the test results of geosim models,

M. 1178, M. 1179 and M. 1180, where the difference of residual current in the larger and the smaller tanks was neglected. (The residual current is larger in the larger tank than in the smaller one.) The experimental data of other models shows smaller $\Delta U/U$ value as shown in Fig. 3, where the difference of residual current was corrected by use of a current meter. At the time of the development of Taniguchi-Tamura's corrector, however, the difference in Fig. 3 was thought to come from with and without the use of side wave killers of the tanks.

Scott's corrector gives rather excessive values in the lower velocity range and does not always coincide with the experimental results in whole tendency. The correction for wave resistance causes sometimes discrepancy, since it is not made on the base of $F_h(=U\sqrt{gh})$ but $F_{nL}(=U/\sqrt{gL})$. Thus, in the case of the smaller model, M. 1720, the correction on wave resistance starts rather lower F_{nL} range and expands rapidly by the increase of F_{nL}, in comparison with the experimental results.

This is the same for the case of Kim's corrector. The author thinks that the reason why the correction factor K introduced by Kim gives so much wavy character on the base of F_{nL} as shown in Fig. 2 also comes from this defect.

It may be said that both Schuster's and Tamura's correctors give adequate correction to the experiments as a whole.

Ogiwara's corrector gives almost the same tendency as above except for such a model with high block coefficient as M. 2058, where the correction becomes overestimate.

The correction by Landweber-Nakayama's corrector, u_1 gives underestimate, as it coincides with the almost lower limit of the experimental results.

5. Concluding Remarks

The studies on blockage effect are historically reviewed by dividing them into three stages, such as "initial", "developmental" and "applicable" ones. The twelve blockage correctors are referred and explained, which belong mainly to the "applicable" stage.

The nine correctors, out of twelve, are applied to the experimental data, which were obtained in the Nagasaki Tank, MHI, compared with each other and evaluated their effectiveness. It may be concluded, as far as in the present comparison, that both Schuster' and Tamura's correctors give adequate correction as a whole.

The studies on this theme seems to be depressed after nineteen-eighties, however its importance does never decrease. The author would appreciate very much if ITTC could recognize again its importance and encourage further studies worldwidely. In this connection, the author sincerely hopes that the studies based on such a new technology as CFD should be pursued.

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